Tracking in the Super-Cryogenic Liquids:He, LHD, LNe

"There is always room at the bottom"

-R. Feynman, 1962

Bottom: tiny track width, energies, radiative loss, backgrounds, liquid density

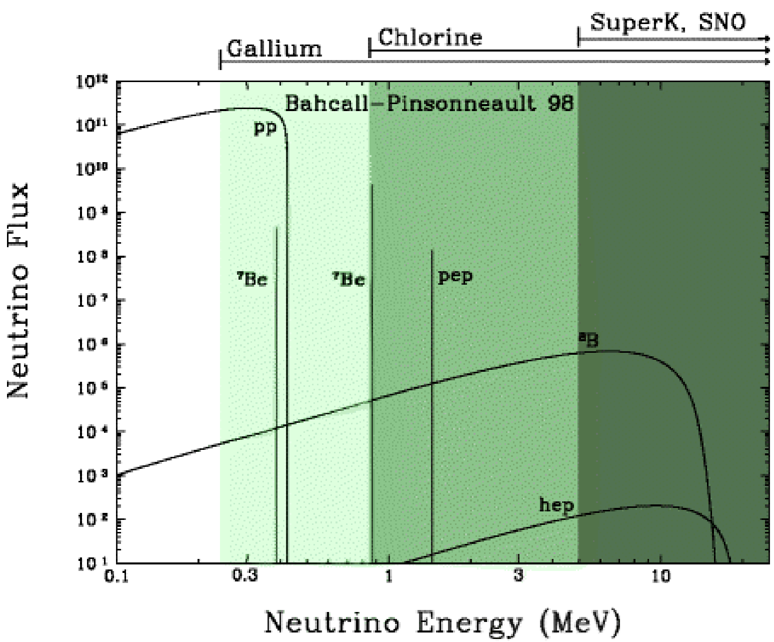
Room: big volume, long smooth tracks clean target interaction, kinematics

http://www.nevis.columbia.edu/~eBubble/

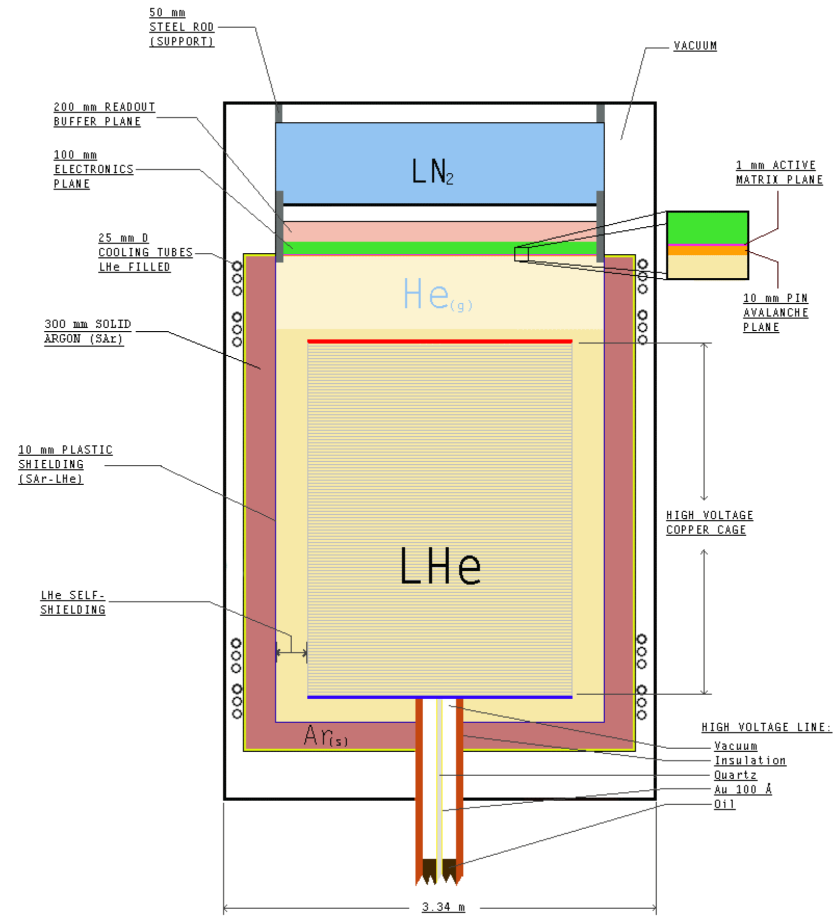
Applications

- **HEP**
  - Low energy n (See LowNu 2002, Bahcall talk)
    - Solar pp reaction neutrinos, E < 423KeV
    - Astrophysical interests
    - Geophysical interests
    - Reactor neutrinos, neutrino magnetic moment
  - High energy neutrinos
    - Full, clean events
    - s, c, b, t identification
    - New particle search (NuTeV events?)
  - Super high energy (LHC) neutrinos
    - Heavy neutrino beams, identification
    - Neutral/charged Currents, etc. with kinematics
    - SUSY-type searches
- **Condensed Matter Physics…Sooner!**
  - Anomalous Charge Carriers, have stumped many stars in the LHe business for a long time, maybe our new techniques can hep. NSF AMOP candidate for help.

Solar Neutrino Spectrum



Solar Neutrino Detector (Concept by H.S. students)



Detector requirement for very low energy neutrino physics

- Fine spatial resolution on sub-MeV tracks
  - For identification of electrons
  - For Range measurements
  - For Compton rejection
  - For track angle measurement
- Good total charge measurement for energy
- At least 5T, 25 m^3 LHe fiducial volume for 1000 solar neutrino events per year
- Low background
- For even lower energies, for neutrino magnetic moment for example, energy resolution is key

The Voxel Challenge

(pixel = 2-D detection element, voxel = 3-D element)

- **We are looking for sub-mm resolution, say 100 microns, so a cubic meter has 10^{12} voxels.**
- **The challenge is to obtain the fundamental resolution, to supply a thinkable detector structure and to read them it.**
- **For a homogeneous medium, one dimension must use a drift, so the resolution is limited by diffusion. The Einstein-Nernst law for thermal diffusion**

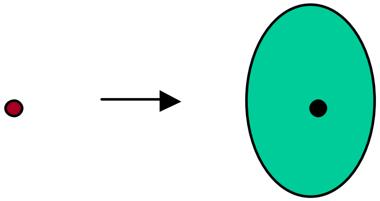
$$s = \sqrt{\frac{2kTd}{eE}}$$

gives us few handles to get the desired resolution once we have fixed, d, the dimension of the detector: seemingly T and E.

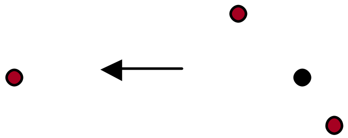
- **Field E cannot be increased much for "free" electrons in noble gases, they "heat up" = become non-thermal; at v_{sat}, T~6000K! !**
- **A massive charge carrier, like an ion, remains thermal for much higher E.**
- **Diffusion is thermally driven; lowering the temperature T cuts diffusion.**
- **The equilibrium negative charge carrier in liquid helium (also hydrogen and neon) is not a free electron, but a 2nm bubble containing the electron (or electrons). The positive carrier is a "snowball" with He^{+} inside, comparable mobility.**
- **We want to track electron-bubbles or snowballs in LHe; they are massive, very low temperature and subject to manipulation by their atomic properties.**
- **The origin of the bubble is a strong (Pauli) repulsion between the electron and the helium atoms. For heavy atoms like Argon, this is compensated by the polarization of the atom.**

Compare L Argon to L Helium, H_2

- **An electron near a large atom:**



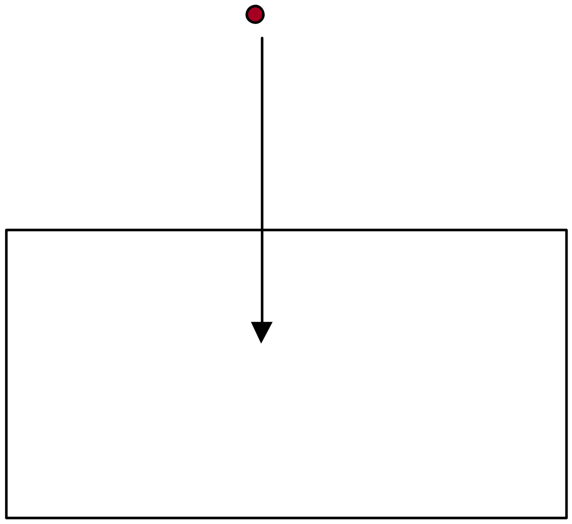
- **An electron near a He/H_2 atom (Pauli)**



Work Functions

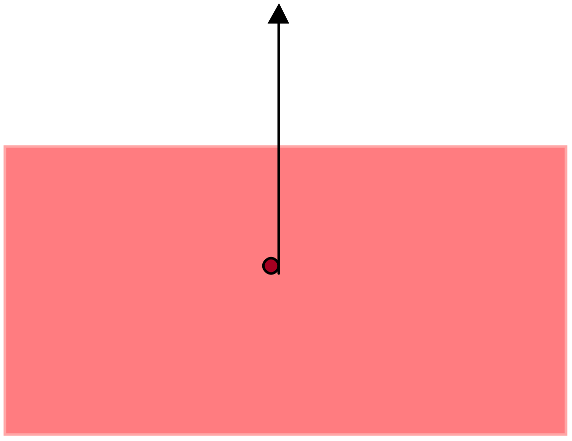
L Argon

W = + 1.4eV



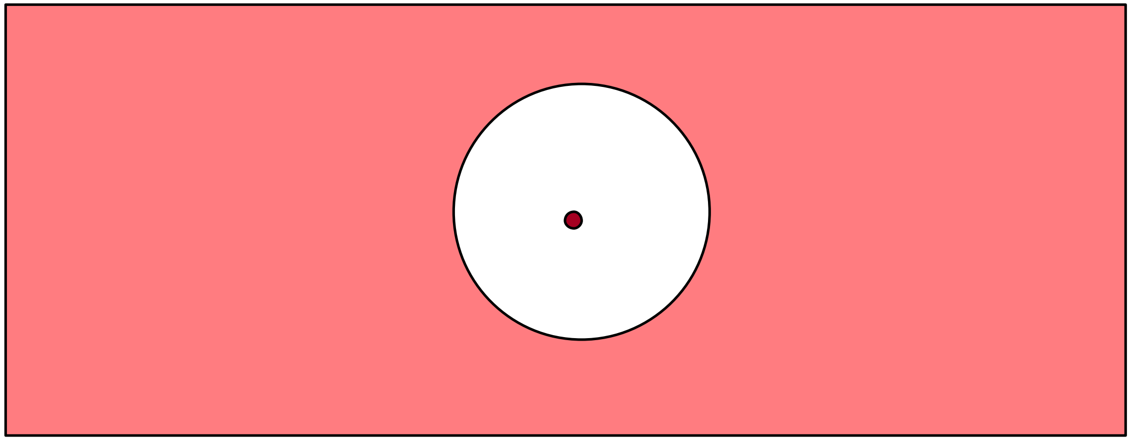
L He

W = - 0.9eV



Fate of an electron in L He

- If an electron is created suddenly in the body of L He in the presence of an electric field, it will start to move with a large mobility as in Argon, but the repulsive force with the liquid will soon blow a hole in the liquid, creating a cavity empty of helium atoms, containing only the electron:

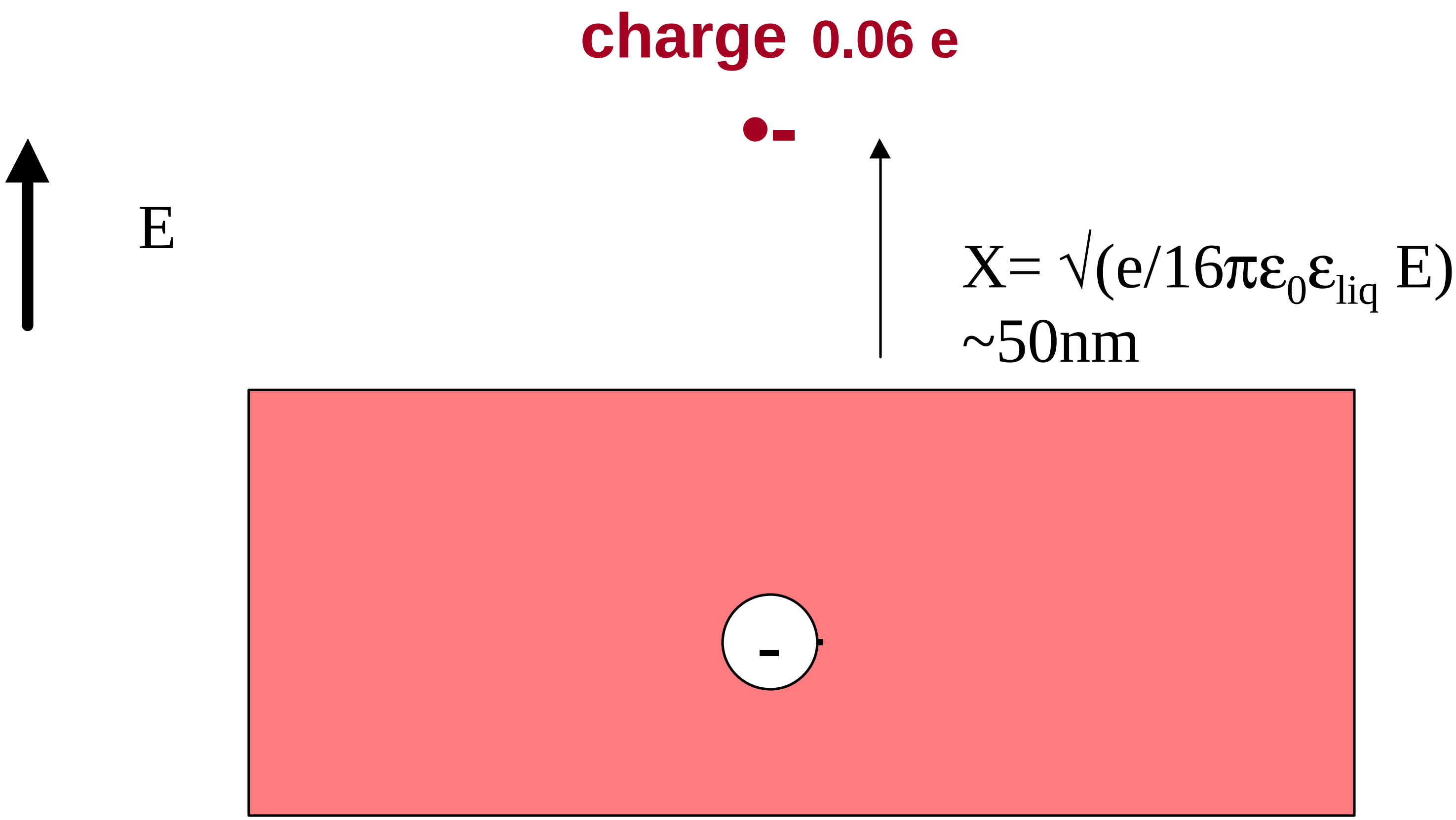


- Scale: nanometers; a “mesoscale” object!

Characteristic of eBubbles

- **Diameter 2nm, i.e. cavity lacking a thousand He.**
- **For E=1KV/mm and T=2K, v=100mm/s, σ = 100μm averaged over 5m drift.**
- **There are ~ 800 bubbles/mm, i.e. order of magnitude denser than grains on tracks in nuclear emulsion $\Rightarrow \sigma = 7\mu$m on 1mm track segment.**
- **eBubble has several <u>resonant absorption</u> lines (E~0.1 and 0.9eV) in the infrared, and strong photoionization, with big cross sections due to the large size of the object, ~10^{-16} cm^2**
- **eBubble remains thermal up to 40KV/cm, field-ionizes around 400KV/cm.**
- **Liquid-gas interface (with repulsive image force) holds the electron for a time dependant on T and E, adjustable from seconds to microseconds, This delay, or photoionization of the eBubble, can be used for optical gating of signals. (There are as yet no satisfactory experimental measurements of the cross sections.)**

Repulsive image force at interface liquid He to gas:



Thermal Diffusion in Helium and Neon

distance	sigma	V / m	T (K)	velocity	N / mm	"+/-" $error_y(z)$
m	µm			cm/s		µm
Helium						
0.01	60.24	2000	4.21	0.4	780	2.16
0.1	190.50	2000	4.21	0.4	780	6.82
1	602.41	2000	4.21	0.4	780	21.57
10	1905.00	2000	4.21	0.4	780	68.21
100	6024.13	2000	4.21	0.4	780	215.70
0.01	19.05	20000	4.21	4	780	0.68
0.1	60.24	20000	4.21	4	780	2.16
1	190.50	20000	4.21	4	780	6.82
10	602.41	20000	4.21	4	780	21.57
100	1905.00	20000	4.21	4	780	68.21
0.01	6.02	200000	4.21	40	780	0.22
0.1	19.05	200000	4.21	40	780	0.68
1	60.24	200000	4.21	40	780	2.16
10	190.50	200000	4.21	40	780	6.82
100	602.41	200000	4.21	40	780	21.57
Neon						
0.01	152.84	2000	27.1	0.032	7300	1.79
0.1	483.32	2000	27.1	0.032	7300	5.66
1	1528.40	2000	27.1	0.032	7300	17.89
10	4833.24	2000	27.1	0.032	7300	56.57
100	15284.04	2000	27.1	0.032	7300	178.89
0.01	48.33	20000	27.1	0.32	7300	0.57
0.1	152.84	20000	27.1	0.32	7300	1.79
1	483.32	20000	27.1	0.32	7300	5.66
10	1528.40	20000	27.1	0.32	7300	17.89
100	4833.24	20000	27.1	0.32	7300	56.57
0.01	15.28	200000	27.1	3.2	7300	0.18
0.1	48.33	200000	27.1	3.2	7300	0.57
1	152.84	200000	27.1	3.2	7300	1.79
10	483.32	200000	27.1	3.2	7300	5.66
100	1528.40	200000	27.1	3.2	7300	17.89

Characteristics of Tracks in LHe

- **Density =0.125 gm/cc**
- **Energy loss = 24 KeV/mm minimum ionizing**
- **Range, 100KeV =1.2mm 200KeV=3.6mm 400Kev=11mm**
- **Radiation Length =7550mm**
- **Fit angle to first mm of track, error for 400Kev = 20degrees, for 120KeV = 60 degrees**
- **The last mm of track looks like about 4x minimum**

Low energy backgrounds

- There seems to be no solubility of heavier molecules in LHe. People have tried, but only introduced other elements in the liquid, for mobility measurements for example, by implantation from a beam. The purity of the liquid is expected to be perfect from this point of view, and we do not expect attachment in long drifts.
- Humphrey Maris has found a monitor (cavitation) for finding "dust" (usually air) in LHe at a very low level. He found that micropore filters gave "atomically clean" liquid. This seems to eliminate embedded sources of radioactive decays.
- Adjacent electronics is probably the main internal source. Item by item study seems to be the only approach.
- (Solid) Nitrogen shielding is effective against the radiation from the main cryostat wall, added to water shielding radiation from the external world.
- Neutron initiated events will be recognized by the range and total ionization of tracks.

- **The good energy and spatial resolution and large size give a powerful capability for recognizing “Compton clusters,” chains of scatterings initiated by photons entering from outside. Each secondary photon from successive scatters has a lower energy, and a decreased absorption length, leading to events with a number of scattering vertices easily recognized as a Compton cluster.**
- **There can still be events where a high energy photon (~1MeV) enters and scatters only once, giving a low energy electron recoil, accepted as a neutrino-electron scattering. Calculations by Valeri Tcherniatine calculated the rejection by cluster recognition, of the order of hundreds, depending on the source.**
- **Summer student Adam Levine followed up, calculating the equilibrium distribution of photons emitted by U and Th and all decay products. After filtering with water and nitrogen shielding, 95% of the photons reaching the detector are from the 2.614 MeV line from Thorium daughter Tl^{208}, at seven per day (reduced from 40 million). The cluster cut and angle cuts can bring backgrounds to low levels. It would seem that the background rates go down with energy. This is important is measuring n magnetic moment.**
- **Also important is that the recognized clusters allow one to measure accurately the photon background as a function of position, energy, angle and time.**

Readout!

- Consider $100m^3$ with 6m drift in a Solar Neutrino Detector: there are 10^{14} voxels to read for 0.1mm resolution element.
- Drift at 10 cm/s through 6m in 60 seconds.
- We see the slow drift time is very useful! Our signals are stored in the detector volume and we deal with them one plane at a time, every millisecond.
- Zero suppression reduces this to < a few kHz.
- The readout plane must then sample 10^9 pixels/ms (for 10 m^2)
- Options for readout plane:
  - Baseline: direct 2^D pixels with active matrix.
  - Serialized by optical gating
    - Photo-ionization of eBubble
    - Photo-excitation of electron across liquid/vapor interface

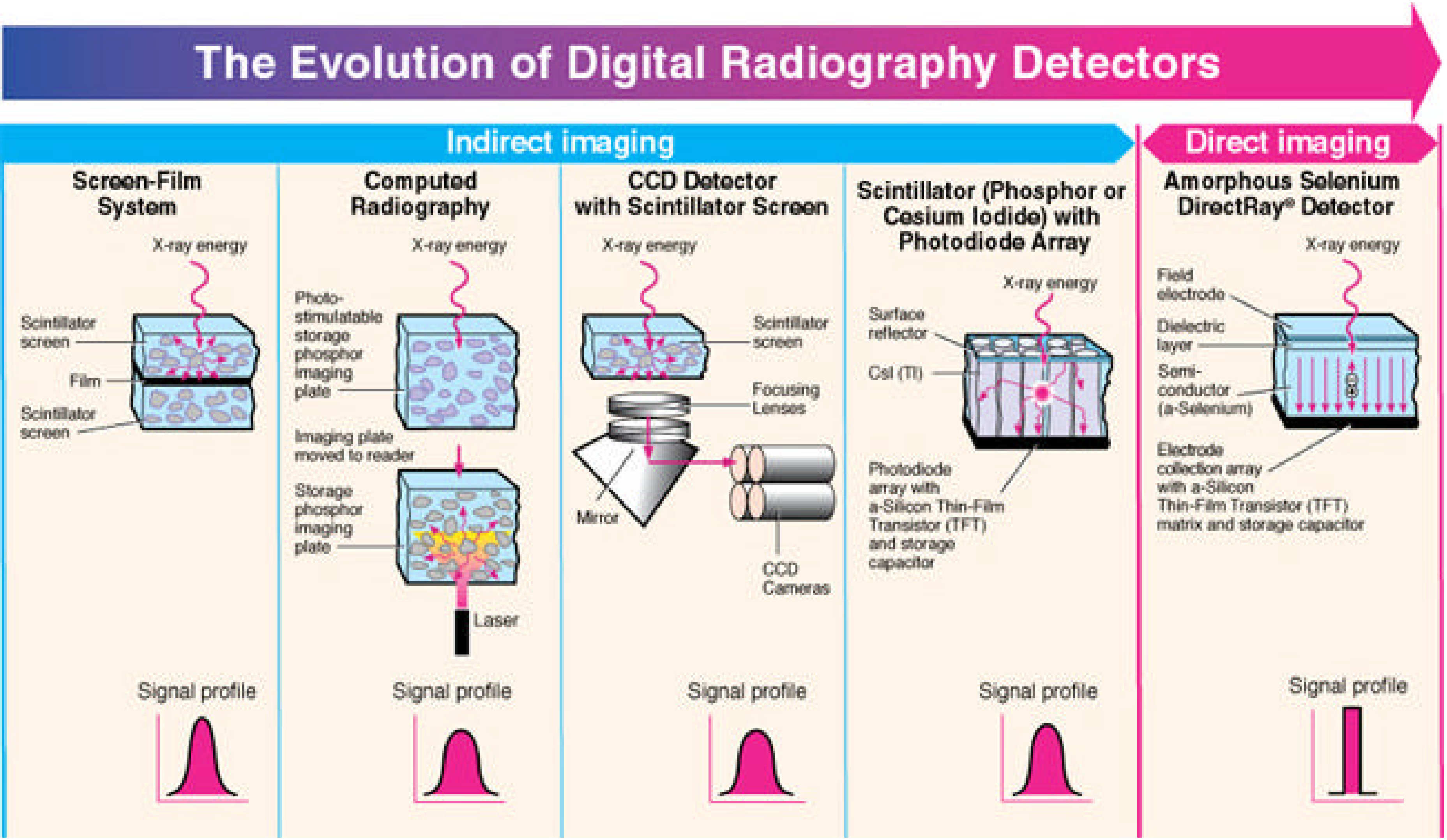
Baseline Readout: 2^D Active Matrix Pixels

- Pavel has been working on a number of aspects (we like this technique for the ATLAS Upgrade, where funding is supposed to start next year)
- Test performance of CMOS at 4K, urgent!!
- Charge enters the sensing plane through a new invention, the Rehak Grid, a 2^D pattern that approximates the 3^D field form of a Frisch Grid: easy to fabricate, rugged, no dead supports, anti-microphonic. (We hope it will support the needed fields.)
- Signal integration time 1 millisecond.
- XY matrix readout
- Noise: low?
- Power: low?

Commercial direct charge detection active matrix: Digital x-ray by Hologic, sells to Kodak

14” by 17” with 140 micron Nyquist resolution, OEM price about $80K, many delivered

Many publications on Hologic site:



Alternatives to the Baseline:

- **Why?**
  - **Maybe we cannot get 4K CMOS or practical alternative. Then we need many fewer connections (by factor of 10^4 say) so that we can back off into gas by some cm.**
  - **Maybe the power is too high to stick in the liquid. Then back off as above.**
  - **Maybe cost will be the issue.**
  - **Maybe we need some shielding against electronics radioactivity.**
  - **Maybe we don’t make enough progress on noise with long (1 millisecond) shaping times.**
  - **Maybe we want avalanche gain in gas.**

Optical gating

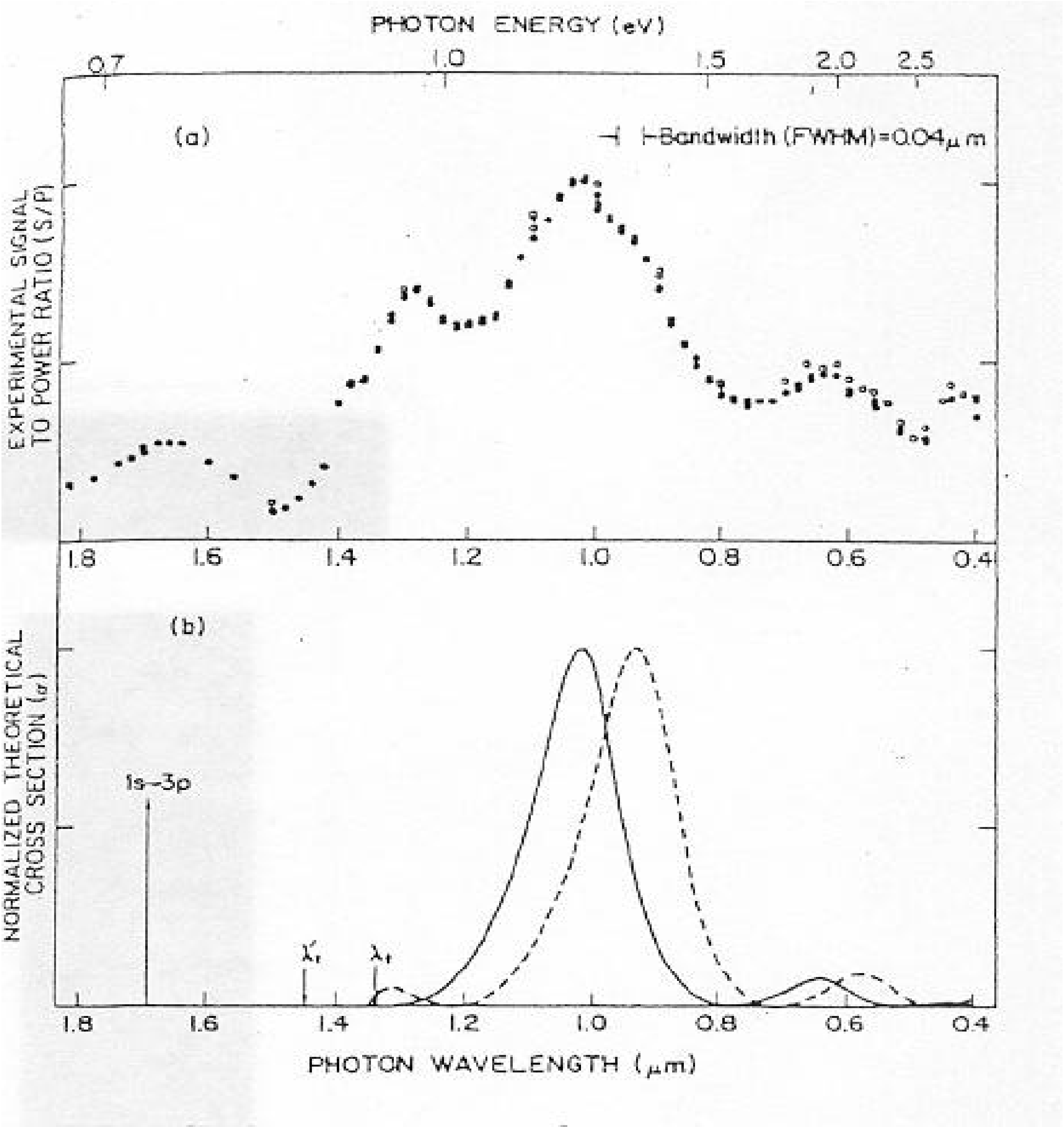
- **Idea: use the ability to manipulate, by light. the electron in its bubble, or trapped at the liquid/vapor interface, to deliver a voxel worth of charge into the Rehak grid (in liquid) or Frisch grid (in vapor) in 100ns, at a known location at a given time, avoiding long integration time problems. (note Sandweiss and Majka did something like this 20 years ago, trapping electrons to negative ions, gating them free with a laser, after the needed delay.)**
- **Each channel can handle 10^4 pixels=1ms/100ns.**
- **in 1ms we can sweep an optical line of width 100mm across 1m, ^ to 10,000 anodes/m each 1m long, with a 100ns shaping on each, covering one square meter. There are ten of these modules in the readout plane, for a total of 100,000 readout lines, each at 10MHz, or 1 THz total.**

Ionize eBubbles with near-infrared light

- **Sweep a narrow line across the readout plane at 1000m/s, resting on each resolution element for 100 ns, freeing the electron from its bubble, just as it is entering into the region of increased electric field in the Rehak Grid.**
- **Keep it free for 100ns, with light if need be.**
- **If there is charge in that voxel, it will be detected on the anode wire, and by the time we know where it was along the scan.**
- **No one has measured the velocity of free electrons, but by extrapolation from other liquified noble gases, we can estimate the saturated velocity to be about 4 10^6 cm/s, or about 2 10^5 cm/s at the 1V/micron in the Rehak Grid, sufficient to move about 200 microns in 100ns, if the electron is always free. Will it stay free, once ionized? What is the lifetime of a free electron in a certain field with a certain light intensity?**

This has been tried, sort of:

Photoejection of Electrons from Bubble States in Liquid Helium, by J. Northby and T. Sanders



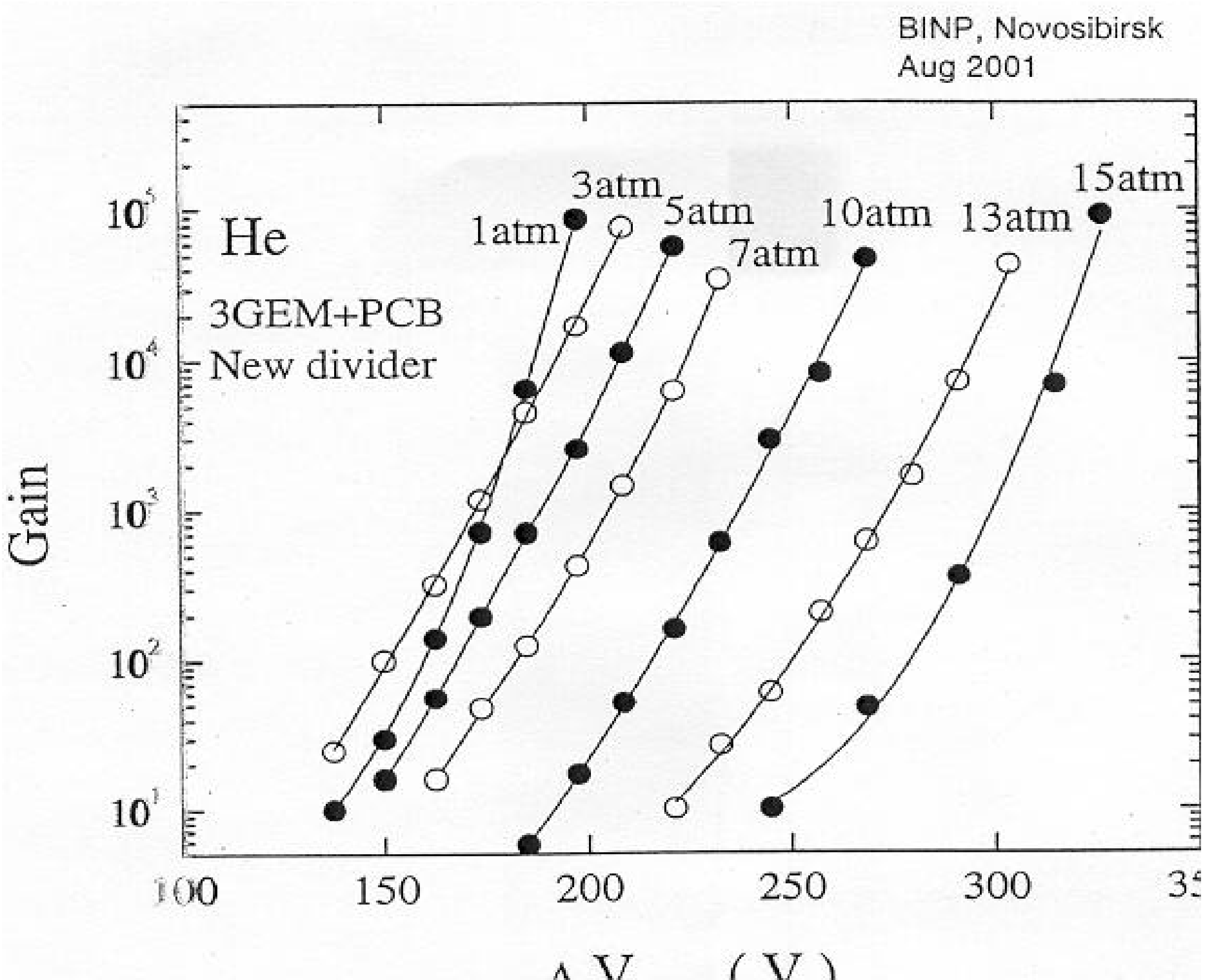
- **The trouble is that the electrons should not have remained free in that measurement, so that are looking at something else. There has been a lot of discussion in the literature about just what effect was being measured, though people cheerfully interpret the peak positions in terms of the levels in the electron bubbles.**
- **We will have to measure more cleanly in the conditions in which we are interested.**
- **Meanwhile, when I try to calculate the power needed from the estimates I have available, I conclude that it is too high by a few orders of magnitude. But there are too many unknown factors. Measurements are required.**

Gating the liquid/vapor interface

- **There are measurements by Rayfield that study the range of temperatures and fields that give delay times of the order of a second.**
- **The dependence on those parameters shows that the process is a combination of tunneling and thermal activation; neither dominates.**
- **It appears that one could choose temperatures around 2K and fields similar to our drift fields to set the delay time to 1ms.**
- **Then light could be used to clear a voxel in 100ns.**
- **The process will be a combination of photoelectric effect and heating, since both have a strong effect on trapping. The scale of the dipole is such that the geometrical cross section is more than three orders of magnitude larger than for eBubble photoionization. Far infra-red photons have the appropriate energy, such as those from the CO_2 laser. Short pulse, multiphoton effects look to be particularly effective, both in collective motion and heating. This could be an effective proposition.**
- **Only one short pulse is needed; once the electron is in the vapor, it is a home run. This lowers the power needed very much, in the standard model. This also means that there is no pressure toward a high field in the Grid region.**

With extraction into vapor, we are set for gain:

Our collaborator A. Buzulutzkov has investigated GEM in high pressure He, to simulate the high density at low temperature. In He, unlike common gases, the performance holds up at high pressure:



We need key physical measurements to move forward, as well as real experience: a Prototype has been constructed on the 10 cm scale:

- **Five windows transmitting from the infra-red to the UV**
- **HV feedthroughs**
- **Signal feedthroughs**
- **Temperature and pressure over a wide range, down to ~1K and up to several atmospheres (the eBubble is quite compressible and allows tuning of parameters by varying the bubble radius)**
- **A field cage for uniform drift field**
- **A photoelectric source for accurately time current pulses**
- **Alpha and spontaneous fission source planned**

Early program of measurements planned for tracking studies

- First cooldown with chamber mounted, including performance of CMOS electronics
- Commission sources and measure drift speed as function of parameters
- Measure ion yields on different sources
- Photoionize drifting cloud, measure power required, free electron velocity and lifetime
- Lower liquid level, map delay time down to millisecond times
- Study photo ejection at liquid/vapor interface
- If all goes well, move toward tracking…

We have opportunities to carry out measurements long needed in Liquid Helium physics. We have looked at how they would fit into our tracking studies:

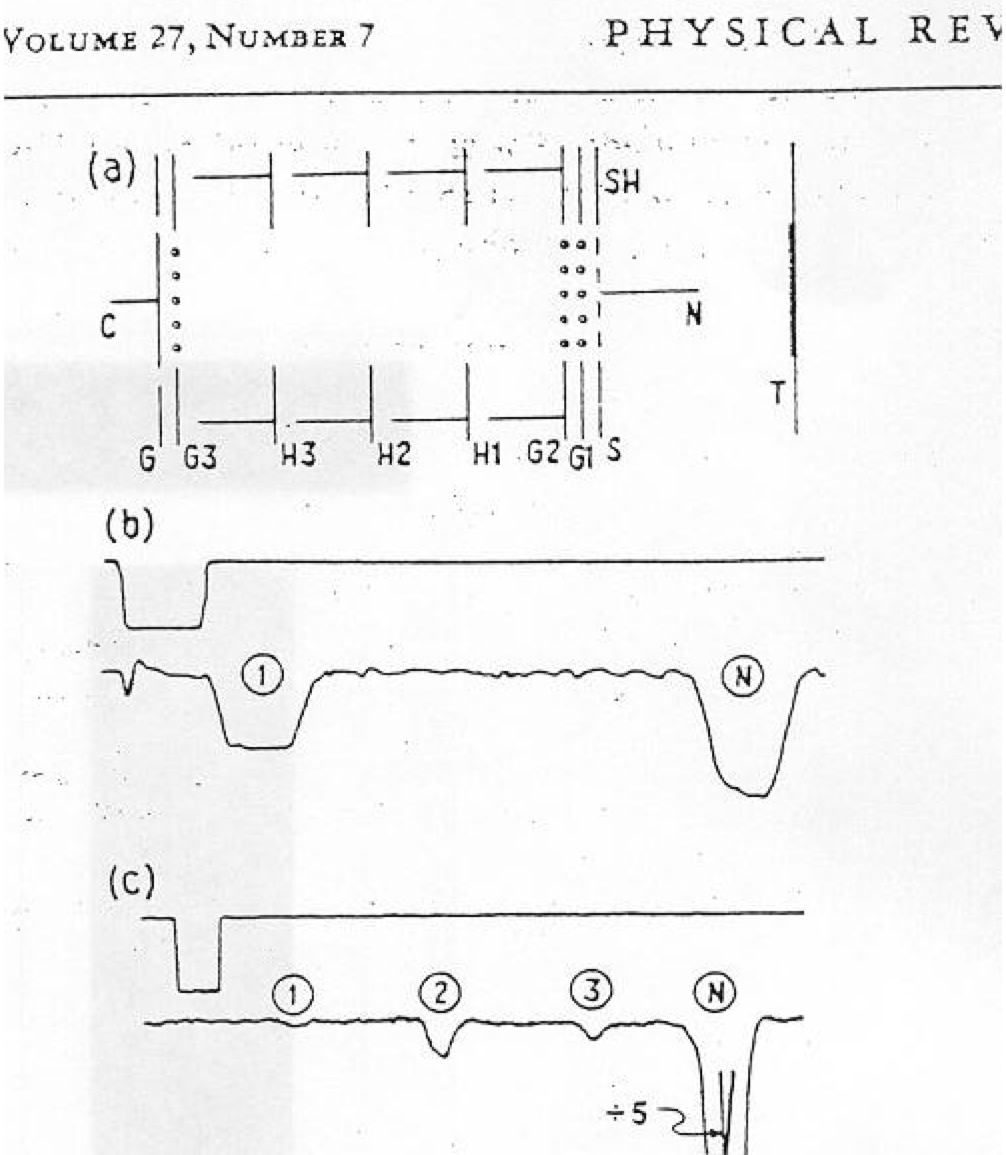
Table

Measurement	Detector R&D	Physics Goals
Drift velocity of eBubble, as a function of E, T, P[i]	Commission cryostat, electronics, HV cage; measure convection	Modest; increase range of P?
Charge yield from alpha source[ii] (⊕?)	Extrapolate Free Ion Yield	Novel test of Onsager-type theory, observation of the anomalous mobility states.[iii]
Trigger on cosmic muons[iv]	Free ion yield on min. ionizing tracks.	Compare with F.I.Y. in gas.
Extraction of e into vapor phase[v] (⊕ if gas gain device is installed)	Tracking readout schemes.[vi]	Much improved study of trapping[vii]
2nd "red" flash[viii] to ionize eBubbles[ix], variable intensity, wavelength.	Possible track readout by light scanning, parameters.	Cross-section vs. wavelength, electron mobility[x].
Short red laser pulse, for example when charge is in high field region.	Track manipulation at low average power.	Measure lifetime of delocalized state as a function of static field, two photon ionization.
Two-laser excitations	For better spatial definition of scanning beam.	Two photon processes in the eBubble.
Heavily ionizing tracks[xi] and multi-electron bubbles. ⊕	Search for characteristic features, possibly anomalous mobilities, allowing tagging of dark matter interactions.	States with many electrons, but few enough so that the individual quantum states will be very interesting when finally observed[xii].
Magnetic properties of multi-electron bubbles. ⊕	**?**	Explore the states of this unusual "atom"
3-D readout, with 2-D plane. ⊕	**Real tracking!** After best readout strategy is determined.	This would offer an unusual tool for tracking superconducting vortex lines. If combined with multi-electron bubbles or other anomalous carriers, it would give a rich new area of physics for those interesting in liquid helium.

One item that has been discussed for decades without resolution

a typical paper: "Exotic Carriers in Liquid Helium"

G. Ihas and T. Sanders



What is this exotic carrier?

- **It seems that they never show up with a beta source, but do show with alphas or other high current sources.**
- **Sanders published a paper trying to show that they are multiple electron bubbles.**
- **Topological structures with one or more electrons?**
- **Humphrey Maris likes to argue that they are quantum entangled states of some obscure sort.**
- **Veit Elser published a paper showing that Maris' paper is wrong, but he himself thinks the data show something unusual, can't imagine what it is.**
- **PRL January 2003 has new data by Maris, the saga continues.**

Sanders Plaint in PRL

ber. This would make the vacuum magnetic quenching theory inapplicable.

Finally we must note that when the liquid level in the cell is lowered still further, until it is between the source and source grid, qualitatively new phenomena appear. The normal-ion pulse becomes very strong, the fast-ion pulse becomes very weak, and a series of pulses of intermediate transit times appears. A recorder trace taken under these conditions is shown in Fig. 1(c). These appear to be genuine charged-particle signals; their mobilities are plotted versus temperature in Fig. 2, curves 2 and 3. Negative carriers with still different mobilities have also been observed. These might be bubbles containing either electrons alone or combined with excited states of the helium atom (such as other substates of the ^4P complex), or some undreamed-of new species. The catalog of charge carriers in liquid helium may be far richer than we have known (or would wish). As a final observation we note that when polarities in the cell are reversed we observe only the usual positive-ion pulse; no anomalous positive carriers have been detected in these experiments.

We are indebted to C. M. Surko and C.-W. Woo

What is needed to settle some of these issues?

- A good example is that we do not know what the unit charge of any of the carriers is. The normal is assumed to have unit charge, but not known by measurement.
- The “fast” anomalous carrier is thought by Sanders to have charge two, by Maris to have charge ½ (!), but it is not measured.
- We can resolve the drift clumps, but people have not distinguished the factors of number of carriers and charge. They measure the product.
- We ought to measure the correlation, event by event, between the two carrier peaks; of course if one can detect single charges it would be easy.
- Avalanche gain would do this.

Similarly with excitation with light beam

- No one has seen the electrons from photoionization.
- We should be able to target a clump, see it turn into electrons, drift (fast) and decay back to eB
- When we target the anomalous carriers with light, will be see them break up or what else? What will be the threshold for effects in power and wavelength?

Summary

- We have some nice equipment.
- We have several options for a solution to the tracking goal.
- A range of interesting neutrino physics problems would benefit from these tracking detectors, at high energies as well as low.
- Our investment has produced instrumentation that has not be available to the condensed matter folk up to now. Maybe we can solve some outstanding problems.
  - And it can be done soon, with the setup we have.

Collaborators & Consultants

Lin Jia, Veljko Radeka, Pavel Rehak, Valeri Tcherniatine, John Warren…BNL

Jeremy Dodd, Yonglin Ju, Richard Friedberg, Tony Heinz, Michael Leltchouk…Columbia

Visitors:

….

John Martin, University of Toronto, Sampa Bhadra, York University, Bill Metzler, Highland High School, Jennifer Denbow, University of MichiganBen Howell, Columbia University
Manssa Muhammad, Langston UniversityDana Lindemann, Wake Forest University
Geoff Shraga, Bronx High School of ScienceAdam Levine, Scarsdale High School (Harvard '05)Nick Litombe, Fox Lane High SchoolPhil Harris, Byram Hills High School (Cal Tech '05)

eBubble Solar Neutrino Detector